

Characteristics of the magnetosheath electron boundary layer under northward interplanetary magnetic field: Implications for high-latitude reconnection

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[1] We analyze Cluster data to explore the statistical properties of the magnetosheath electron boundary layer, observed outside the high-latitude dayside magnetopause, under northward interplanetary magnetic field (IMF). We investigate the dependence of the presence and directionality of heated magnetosheath electrons in this layer on the geomagnetic dipole tilt and IMF tilt angles. The statistical results illustrate that the dipole tilt angle primarily controls the directionality of heated electrons in the magnetosheath boundary layer outside of the magnetopause. By contrast, the effect of the IMF tilt angle appears marginal. If the presence of such heated electrons is taken to be the signature of magnetosheath field lines that have reconnected with the high-latitude magnetic field of the Earth, tailward of the cusp, these results indicate that the dipole tilt determines in which hemisphere high-latitude reconnection of a given magnetosheath field line occurs first. The marginal impact of the IMF tilt angle may indicate that its potential effect is partially removed by the IMF passage through the bow shock and subsequent magnetic field draping at the dayside magnetopause. The frequent detection of bidirectional heated electrons outside the magnetopause additionally suggests that magnetosheath field lines may frequently reconnect in both hemispheres. Such a finding would support double high-latitude reconnection as a potential mechanism for low-latitude boundary layer formation under northward IMF.

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1. Introduction

[2] The magnetic field topology arising from the occurrence of magnetic reconnection at the Earth's magnetopause results in the presence of a boundary layer, inside the magnetopause, and containing a mixture of magnetosheath and magnetospheric plasmas [e.g., *Eastman and Hones*, 1979; *Ogilvie et al.*, 1984; *Mitchell et al.*, 1987; *Hall et al.*, 1991]. This topology also results in the presence of a magnetosheath boundary layer on the outside of the magnetopause. Field lines in this latter region are magnetically connected to the open magnetopause, and typical signatures in this layer are the presence

of leaking magnetospheric particles as well as heated magnetosheath plasma, interpreted as having twice passed through the reconnected magnetopause [*Fuselier et al.*, 1997].

[3] Under northward IMF, high-latitude reconnection occurs between the magnetosheath and lobe magnetic field lines [*Gosling et al.*, 1991; *Kessel et al.*, 1996]. Because it may occur at both the northern and southern hemispheres, *Song and Russell* [1992] proposed the creation of newly closed magnetospheric field lines at the dayside magnetopause when the IMF is strongly oriented northward. This prediction was later supported by case studies [*Le et al.*, 1996; *Onsager et al.*, 2001] and MHD simulations [*Raeder et al.*, 1997].

[4] *Onsager et al.* [2001] particularly focused on the presence of heated magnetosheath electrons streaming in the magnetosheath boundary layer, outside the magnetopause at high latitudes, under northward IMF. On the basis of a case study, they showed that the directionality of the heated electrons may be the signature of whether high-latitude reconnection has already occurred in one or the other, or both, hemispheres. However, it is not known what geophysical parameters actually control which hemisphere may reconnect first.

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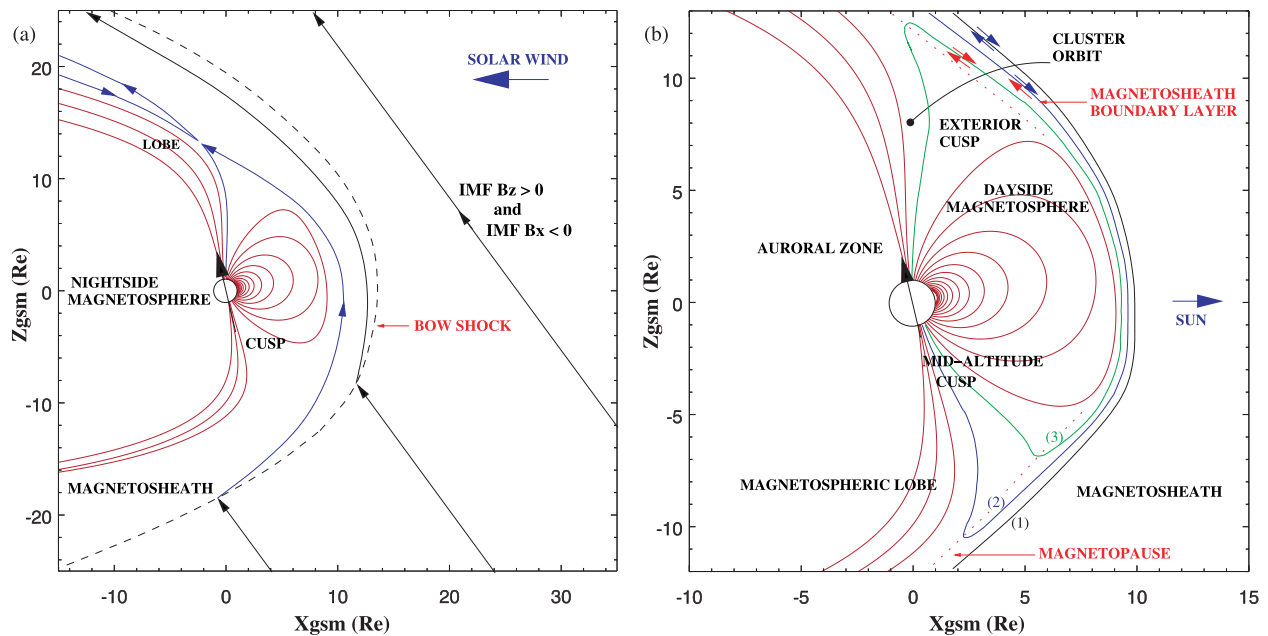


Figure 1. (a) Illustration of solar wind field line traversal of the bow shock and transport toward the high-latitude magnetopause. This illustration shows a case of northward and tailward interplanetary magnetic field (IMF) orientation (negative IMF tilt angle), together with a negative geomagnetic dipole tilt. Such an IMF orientation could favor reconnection occurring first at the high-latitude magnetopause in the northern hemisphere. (b) Sketch of Cluster passage through the high-latitude magnetopause and magnetosheath boundary layer. It shows a northward IMF case with highly draped magnetosheath field lines. The negative dipole tilt angle here leads to reconnection occurring first in the southern hemisphere. In this sketch, the strong draping of magnetosheath field lines implies that the dipole tilt angle is the major factor controlling which hemisphere reconnects first. The blue arrows adjacent to the field lines numbered 1 and 2 illustrate the presence of streaming, cold magnetosheath electrons. The red arrows, on field lines 2 and 3, correspond to streaming heated electrons (see text).

[5] Figures 1a and 1b illustrate the possible influence of the IMF tilt angle ($\tan^{-1}(B_x/B_z)$) and geomagnetic dipole tilt angle on the location (hemisphere) of reconnection of a given magnetosheath field line under northward IMF. The sketch in Figure 1a suggests that if the reconnection occurrence rate is high (as recently reported by *Twitty et al.* [2004]), a negative IMF tilt angle may lead to reconnection in the northern hemisphere first (blue line). Figure 1b shows the probable effect of the dipole tilt angle. In this case, the negative dipole tilt would lead to magnetosheath field lines reconnecting first in the southern hemisphere (field line labeled 2). If magnetosheath field lines are highly draped along the dayside magnetopause (field line 1), the effect of the IMF tilt angle may be partially suppressed and, as shown in the sketch of Figure 1b, the dipole tilt may have a dominant effect on the hemisphere of initial reconnection. The same field line may later reconnect in the second hemisphere and create a newly closed field line (field line 3), as envisaged by *Song and Russell* [1992] and *Onsager et al.* [2001].

[6] Here we concentrate on the statistical dependence of the directionality of the heated electrons in the magnetosheath boundary layer in order to discriminate between the concurrent effects of the geomagnetic dipole tilt and IMF tilt angle. We further report on the apparent occurrence of bidirectional heated electrons outside the

magnetopause, which is a possible signature of double high-latitude reconnection.

2. Instrumentation and Event Illustration

2.1. Instrumentation

[7] In this study, we primarily make use of electron data from the PEACE (Plasma Electron and Current Experiment) instrument on board the Cluster spacecraft [*Johnstone et al.*, 1997; *Szita et al.*, 2001]. We show data from both the LEEA (Low Energy Electron Analyzer) and HEEA (High Energy Electron Analyzer) sensors, with typical respective energy ranges from 0.6 eV to 1 keV and 35 eV to 26 keV. Cluster Ion Spectrometer/Hot Ion Analyser (CIS/HIA; *Rème et al.* [2001]) and Fluxgate Magnetometer (FGM; *Balogh et al.* [2001]) data are also used for magnetopause identification and are shown for illustration in section 2.3.

2.2. Origin and Properties of the Magnetosheath Electron Boundary Layer

[8] *Russell et al.* [2000], *Onsager et al.* [2001], and *Lavraud et al.* [2002, 2004a] have emphasized that several distinct boundaries may exist in the vicinity of the exterior cusp region. In the present paper, we define the magnetopause as the outermost boundary with the magnetosheath (c.f. Figure 1 and above references).

[9] Magnetosheath electrons are known to be heated upon traversal of the magnetopause rotational discontinuity (RD) [Paschmann *et al.*, 1993; Onsager *et al.*, 2001]. Because these electrons are fast, they can mirror at low altitudes and escape back through the magnetopause to form an observable outside layer of hotter magnetosheath-like electrons streaming away from the open magnetopause [Fuselier *et al.*, 1997].

[10] Figure 1b shows a typical Cluster trajectory through the dayside magnetosphere outbound into the magnetosheath. Recall that the figure depicts a case of northward IMF and negative dipole tilt angle. The small arrows attached to the field lines labeled 1, 2, and 3 represent heated (red) and pristine, cold (blue) streaming magnetosheath electrons outside the magnetopause. As suggested by Onsager *et al.* [2001], once an outbound spacecraft has crossed the dayside magnetopause under northward IMF, it may encounter three main types of magnetic field lines (Figure 1b): (1) magnetosheath field lines (black) not connected to the Earth, which are only populated by pristine, cold magnetosheath electrons in all directions, (2) field lines having one end connected to the ionosphere and the other to the solar wind (blue) and showing heated electrons streaming in only one direction, and (3) newly closed field lines connected to both the northern and southern ionospheres (green), which show heated electrons streaming in both the parallel and antiparallel directions.

[11] In such a context, the identification of the magnetopause is of crucial importance. The magnetic field cannot be used in the case of the high-latitude magnetopause under northward IMF because of the lack of clear shear in the magnetic field observations for most cases. The magnetic shear may be large at high latitudes close to the reconnection site, but at somewhat lower latitudes the magnetopause crossings often exhibit a low magnetic shear, and magnetopause identification is difficult.

[12] Our working definition of the magnetopause in this study is based on the ion temperature. Ions are also heated upon their traversal of the high-latitude magnetopause under northward IMF [Lavraud *et al.*, 2002]. However, because of their mass, ions are much slower and form a very much thinner layer outside of the magnetopause than that described above for the electrons. This spatial structure results from a velocity filter effect following from sunward plasma convection after the onset of magnetic reconnection at the high-latitude magnetopause. Therefore using ion temperature as an indicator of the magnetopause simply means that when ion temperature is low (but that of electrons is still high), the spacecraft is sampling the outermost part of the magnetopause structure where only heated electrons have access, i.e., the magnetosheath electron boundary layer.

[13] For the event described below and the statistical survey, we used electron pitch angle data at 4 s resolution in order to discriminate the main directionality of heated magnetosheath electrons found outside the dayside magnetopause. This identification was based on the inspection of the electron spectral width, as compared with the measured ion temperature.

2.3. Event Illustration: Exterior Cusp and Magnetopause

[14] Figure 2 presents Cluster PEACE (from the LEEA sensor), CIS, and FGM observations from spacecraft 3, as

well as ACE IMF data, for the high-latitude magnetopause crossing on 16 March 2002. This event is used here as an illustration because (1) it has been chosen as a potentially interesting event for the GEM 2004 campaign, in the context of the study of the cold, dense plasma sheet formation and (2) it has previously been studied in more detail by Lavraud *et al.* [2004b].

[15] In Figure 2, three spectrograms are shown for electrons flowing parallel, perpendicular, and antiparallel to the magnetic field in Figures 2a, 2b, and 2c, respectively. Figures 2d, 2e, and 2f display the CIS/HIA ion density, velocity components (in GSM coordinates) and perpendicular temperature, respectively. Although the ion measurements present a few data gaps, the coverage is sufficient for the purpose of this illustration. Figure 2g shows FGM magnetic field measurements (GSM), while Figure 2h displays the prevailing (ACE) IMF conditions (GSM) with a lag time of 4500 s.

[16] At the start of the interval, spacecraft 3 was in the exterior cusp region and observed rather high ion temperatures, low magnetic field strengths, and low plasma flows (Figures 2e, 2f, and 2g), which are characteristic of that region under northward IMF conditions [Lavraud *et al.*, 2002, 2004b]. In the exterior cusp, the electrons were observed to be heated in all directions (Figures 2a, 2b, and 2c, according to their spectral width) as compared to the pristine, cold magnetosheath electrons seen after about 0815 UT. This observation is consistent with a location inside of the magnetopause. The exit into the magnetosheath occurred at ~0811:40 UT, as indicated by the first vertical black line in Figure 2 which corresponds to the drop in the ion temperature.

2.4. Event Illustration: Magnetosheath Boundary Layer

[17] In Figure 2, once the spacecraft exited through the magnetopause, in what we have labeled region 3 (corresponding to field line 3 in Figure 1b), the ion temperature, as well as the magnetic field and velocity, were characteristic for the pristine magnetosheath. However, the spacecraft still observed heated magnetosheath electrons in all directions (Figures 2a, 2b, and 2c). Slightly later, however, the electrons became colder in the antiparallel direction (region 2), but the distribution in the parallel direction (panel a) remained nearly as hot as in the exterior cusp and region 3. Several intervals of regions 2 and 3 plasmas were successively observed before a definitive exit into the colder, pristine magnetosheath at ~0814:30 UT. The regions 2 and 3 intervals are thus distinct from the exterior cusp in terms of the ion temperature, flow speed, and magnetic field direction and strength, which are typical for the magnetosheath.

[18] The presence of unidirectional heated electrons in region 2, flowing parallel to the magnetic field, suggests that the magnetic field lines there were connected to the magnetopause in the southern hemisphere. The existence of such a layer of unidirectional heated electrons at the outer edge of the boundary layer (since it is detected after region 3) suggests that the southern hemisphere reconnected first during this interval. The average orientation of the IMF tilt angle (-33.4°) recorded by ACE at that time would perhaps lead one to expect an initial reconnection in the northern hemi-

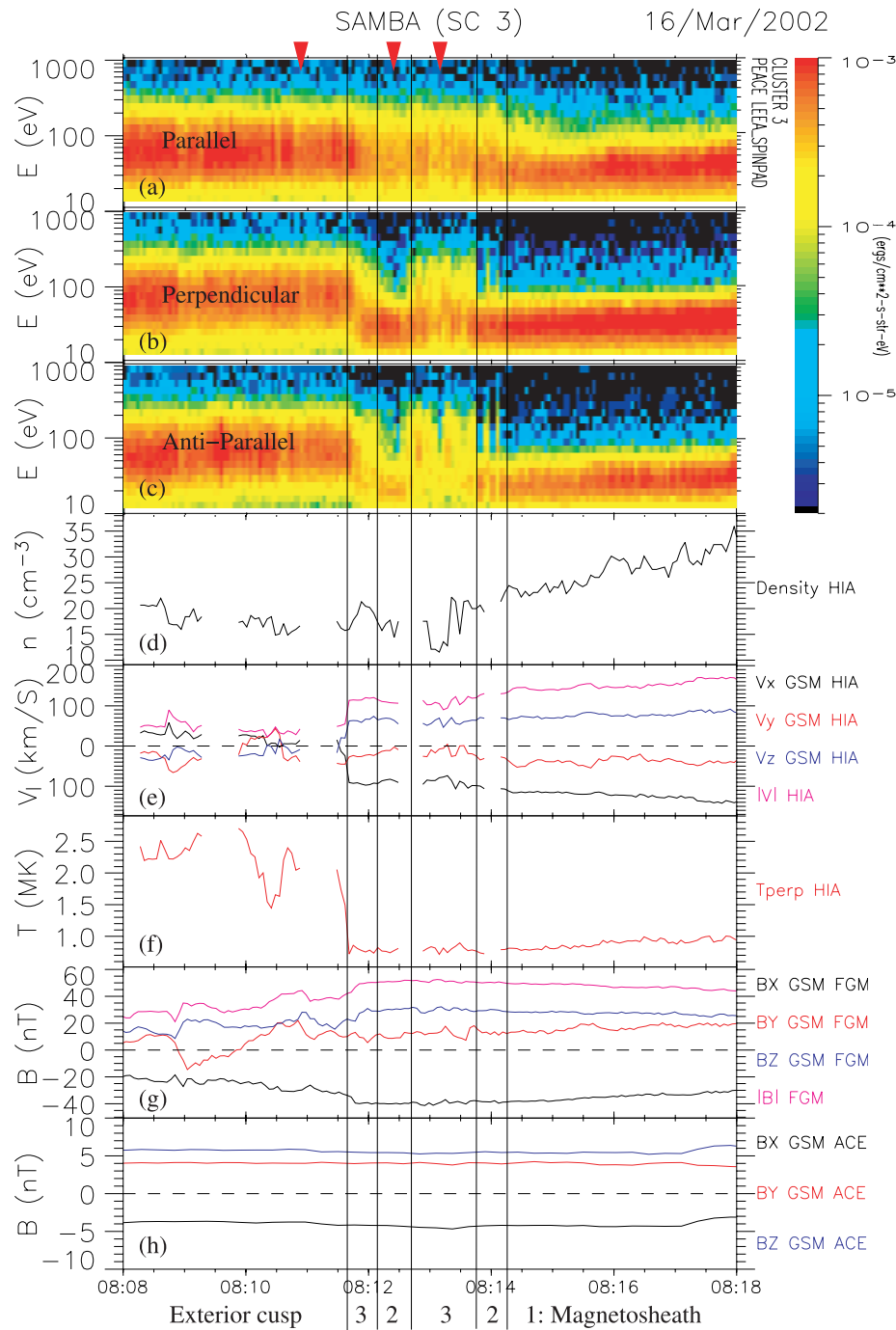


Figure 2. Overview of Cluster spacecraft 3 passage through the high-latitude magnetopause on 16 March 2002. (a–c) The parallel, perpendicular, and antiparallel (energy fluxes) flowing electrons from Plasma Electron and Current Experiment (PEACE)/Low Energy Electron Analyzer (LEEAE). (d–f) The Cluster Ion Spectrometer (CIS)/Hot Ion Analyser (HIA) ion density, velocity components (GSM), and perpendicular temperature. (g) Fluxgate Magnetometer (FGM) magnetic field components (GSM). (h) ACE IMF data (GSM) lagged by 4500 s. See text for region descriptions.

sphere (cf. Figure 1a). However, the magnetic dipole tilt angle was $\sim -8.4^\circ$ at the time of the magnetopause crossing, which is consistent with an initial reconnection in the southern hemisphere (cf. Figure 1b). Finally, the presence of bidirectional heated electrons in region 3 suggests that the magnetic

field there was connected to the open magnetopause in both hemispheres. Thus region 3 potentially represents newly closed field lines outside the magnetopause.

[19] We illustrate these differences in Figure 3. Both Figures 3a and 3b display electron phase-space density

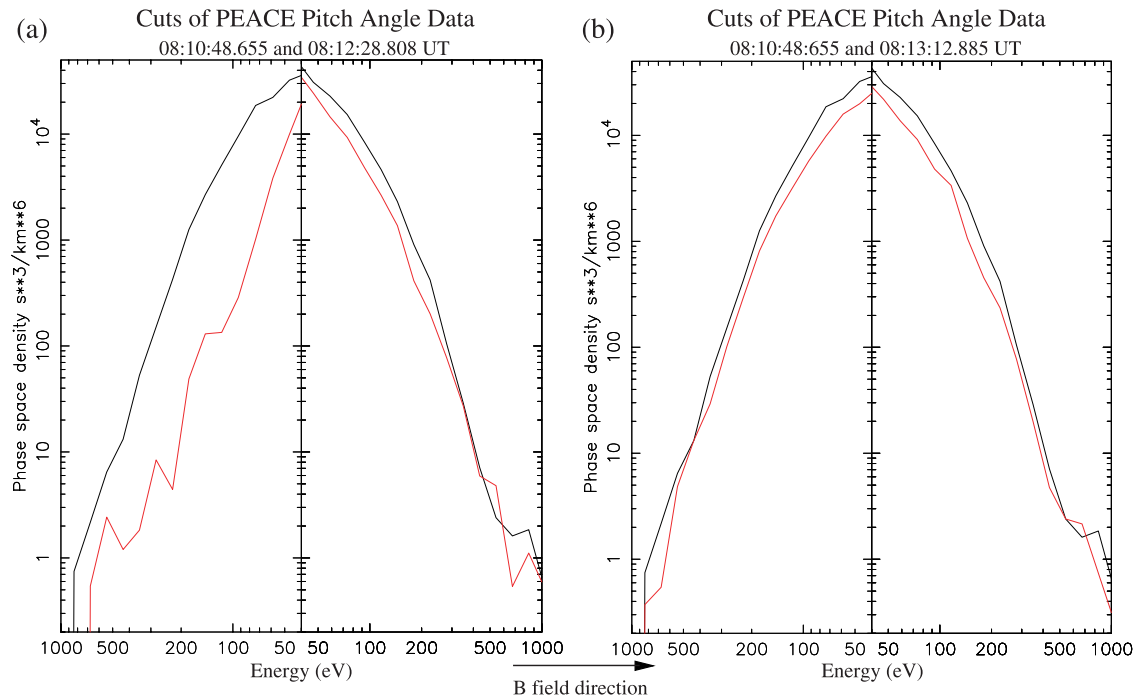


Figure 3. Phase-space density spectra of the electrons from spacecraft 3 in (a) region 2 and (b) 3 compared with that in the exterior cusp region (calculated in the spacecraft frame). These are cuts of the PEACE pitch angle data in the direction parallel (to the right side of each plot) and antiparallel (to the left) to the magnetic field. In both plots, the black line represents the spectrum obtained in the exterior cusp at 0810:57 UT. The red lines in Figures 3a and 3b, show representative spectra obtained in Region 2 (08:12:18 UT) and 3 (08:13:30 UT), respectively. Those three times are marked by red triangles at the top of Figure 2.

spectra (from HEEA sensor) along the direction of the magnetic field, with the right-hand (left-hand) parts of each plot being the parallel (antiparallel) direction. The times corresponding to the spectra are marked by red triangles in Figure 2. The spectrum from the exterior cusp is shown in both Figures 3a and 3b as a black line. Figure 3a reveals that the parallel-flowing electrons in region 2 (red) are nearly as hot as those in the exterior cusp, while the antiparallel component is much colder and magnetosheath-like. Region 3 (red in Figure 3b), by contrast, shows a spectrum more similar to that of the exterior cusp with heated electrons in both the parallel and antiparallel directions.

[20] The observation of heated electrons in one direction together with colder electrons in the opposite direction (region 2) is an unambiguous signature that the spacecraft actually is outside the magnetopause. When inside the magnetopause, as for the exterior cusp or low-latitude boundary layer, the electrons are heated in both the parallel and antiparallel directions [Hall *et al.*, 1991; Paschmann *et al.*, 1993; Phan *et al.*, 1997; Fuselier *et al.*, 1997]. In contrast, the identification of bidirectional heated electrons outside the magnetopause (region 2) is more ambiguous owing to the possibility that the spacecraft actually may observe a partial crossing of the magnetopause at such times. Although the ion temperature, flow speed, and magnetic field provide some discrimination between the two possibilities, in the survey described below the identification of unidirectional heated electrons should be

regarded with greater confidence than that of bidirectional heated populations outside the magnetopause.

3. Statistical Survey and Discussion

3.1. Survey Criteria

[21] On the basis of both magnetic field and ion data we identified all magnetopause crossings over the first 3 years of Cluster operation (2001–2003) for spacecraft 3. We restricted our survey to the months of December through May when the Cluster orbit intersects the dayside magnetopause. Solar wind parameters were determined by time-lagging measurements from the ACE spacecraft. With t_0 being the magnetopause crossing time, we calculated a first lag time $\Delta t_1 = \Delta X/V_X(t_0)$, where ΔX is the GSE X distance between Cluster and ACE and $V_X(t_0)$ the solar wind velocity at time t_0 . We then used a lag time $\Delta t_2 = \Delta X/V_X(t_0 - \Delta t_1)$. When necessary, the lag times were further corrected after visual comparison of the IMF with FGM data in the magnetosheath.

[22] Since we are interested in the possible occurrence, and signatures, of reconnection at the high-latitude magnetopause, we selected magnetopause crossings for which the IMF was both northward and relatively steady. Using a lagged 30-min IMF data interval centered on each magnetopause crossing, we selected the events for which the average IMF clock angle ($\tan^{-1}(B_Y/B_Z)$ in GSM) lay in the range $[-60^\circ, 60^\circ]$ and during which no measurement

Table 1. Magnetopause Crossings and Magnetosheath Electron Boundary Layer Characteristics: Cases of Average Interplanetary Magnetic Field Clock Angle Between -60° and 60° ^a

Date dd/mm/yy	X_{GSM}	Y_{GSM}	Z_{GSM}	MP Time	IMF CA	IMF Tilt	Dipole Tilt	e- dir.	Bi-dir.
<i>Northern Hemisphere</i>									
04/02/01	4.91	1.16	11.01	22:02	-22.9	-17.2	-12.9	P	Yes
16/02/01	7.63	0.16	10.68	20:56	14.7	57.6	-6.3	U	U
22/03/01	7.25	-3.39	8.37	02:48	47.3	7.8	-8.0	P	Yes
26/03/01	8.25	-4.99	7.54	21:53	26.5	-52.8	5.4	U	U
19/04/01	5.72	-3.68	7.95	15:00	-49.3	70.0	21.1	U	U
24/04/01	6.18	-3.99	8.30	09:55	48.2	-20.8	10.9	P (opp)	Yes
01/05/01	7.56	-8.59	6.94	16:00	6.8	-45.5	25.8	P (opp)	Yes
30/12/01	1.31	10.74	7.38	09:55	-38.1	31.9	-25.5	U	Yes
09/01/02	4.98	8.67	11.14	01:14	51.3	-61.1	-27.8	P	U
23/01/02	5.94	6.40	10.29	04:37	-11.7	26.5	-29.7	P	U
02/03/02	7.15	-0.76	9.00	03:31	27.5	44.1	-16.6	P	U
09/03/02	7.12	-0.41	8.72	06:30	39.1	29.5	-13.8	P	Yes
11/03/02	4.68	0.21	8.45	13:47	44.6	-38.7	3.4	P (opp)	U
16/03/02	5.16	-0.23	8.35	08:10	34.6	-33.4	-8.1	P	Yes
18/03/02	1.56	0.07	7.35	14:57	25.2	-33.6	8.7	U	U
02/04/02	6.36	-4.46	6.89	00:22	37.7	-56.1	0.9	U	U
02/05/02	6.32	-8.17	4.99	23:35	41.5	-47.9	13.2	A	Yes
19/05/02	5.52	-13.53	2.59	19:47	26.8	-72.6	27.1	A	U
21/05/02	3.81	-6.58	5.90	22:08	-15.5	-15.5	21.6	A	U
01/03/03	9.12	0.81	8.23	05:20	-13.3	64.4	-17.6	P	Yes
08/03/03	9.50	0.62	7.74	08:55	-22.5	47.8	-9.8	P	Yes
17/03/03	7.30	-2.40	7.42	19:21	3.4	-38.6	7.4	U	U
20/03/03	7.75	-2.00	7.42	04:45	37.4	10.3	-10.4	P	U
03/04/03	7.80	-2.42	7.18	11:15	17.7	41.8	7.1	A	Yes
13/04/03	8.63	-6.38	4.77	00:48	-12.9	-60.7	3.8	A	U
30/05/03	3.63	-6.61	7.51	13:19	20.5	-25.1	28.2	A	Yes
<i>Southern Hemisphere</i>									
20/01/01	11.56	7.87	-3.70	19:05	-25.8	-11.0	-10.8	U	U
04/02/01	6.67	1.17	-7.12	07:20	-33.4	-41.6	-24.3	U	U
04/04/01	2.43	-0.89	-9.09	19:44	-11.3	54.1	13.8	P (opp)	U
03/02/02	4.92	-0.07	-8.23	09:15	-47.7	-54.9	-20.5	U	U
08/02/02	5.60	2.32	-8.10	02:50	27.1	-36.3	-23.5	P	Yes
08/03/02	5.97	-1.38	-9.47	14:37	56.9	-22.1	4.2	A	Yes
10/04/02	1.32	0.03	-10.07	23:11	26.1	-30.7	7.2	A	Yes
07/05/02	0.21	-3.70	-11.68	00:34	-45.3	-23.8	11.8	A	Yes
28/01/03	1.13	-0.71	-7.65	17:20	34.1	-15.6	-7.5	A (opp)	Yes
07/03/03	2.56	-0.25	-9.81	16:45	-50.1	55.2	5.5	A	Yes
26/03/03	-1.02	1.14	-8.39	19:22	-18.5	-46.6	11.0	A	Yes

^aThis table uses the following abbreviations. X_{GSM} , Y_{GSM} and Z_{GSM} : Spacecraft 3 position in GSM at MP time. MP Time: Approximate magnetopause crossing time for spacecraft 3. IMF CA: Average IMF clock angle over the 30 min centered on MP time. IMF Tilt: Average IMF tilt angle over the 30 min centered on MP time. All angles are in degrees. For electron directionality (e-dir.), P: parallel, A: antiparallel, and U: unclear. In six cases the directionality is not compatible with the dipole tilt; these are marked as opposed (opp). Bidirectional electrons (Bi-dir.) are either apparently present outside the magnetopause (Yes) or are unclear (U).

had an absolute clock angle greater than 90° (for steadiness). Thirty-seven events were identified which meet the above criteria and have good data.

[23] The characteristics of these 37 events are listed in Table 1. For each magnetopause crossing we list, from left to right, the date, the magnetopause crossing time, the average IMF clock angle, the average IMF tilt angle in the $(X,Z)_{\text{GSM}}$ plane ($\tan^{-1}(B_X/B_Z)$) (again using a 30-min data interval) and the dipole tilt angle at the time of magnetopause crossing. The sixth column presents the main (uni-) directionality (where P is parallel flow of heated electrons, A is antiparallel, and U is unclear) found in the electron data outside the magnetopause. This corresponds to the directionality of the heated electrons in region 2, if such a region, as described previously and in Figure 1, exists. The last column states whether bi-directional heated electrons are present in the magnetosheath boundary layer outside the magnetopause (region 3 in Figure 1), i.e., when

the ion perpendicular temperature is closer to that of the magnetosheath.

3.2. Dependence on the Dipole Tilt and IMF Tilt Angles

[24] Figure 4a shows the distribution of the occurrence of unidirectional heated electrons in a scatterplot of the dipole tilt and IMF tilt angles, for each of the 37 crossings. In this figure, the open (filled) circles represent the cases of unidirectional heated electrons flowing parallel (antiparallel) to the magnetic field. Parallel flow of heated electrons is expected if the initial reconnection site lies in the southern hemisphere, whereas antiparallel flow would result from reconnection initiating first in the northern hemisphere. The open triangles correspond to events for which no clear directionality was found.

[25] Out of 37 events, ten show unclear main directionality. For the 27 events where clear directionality was

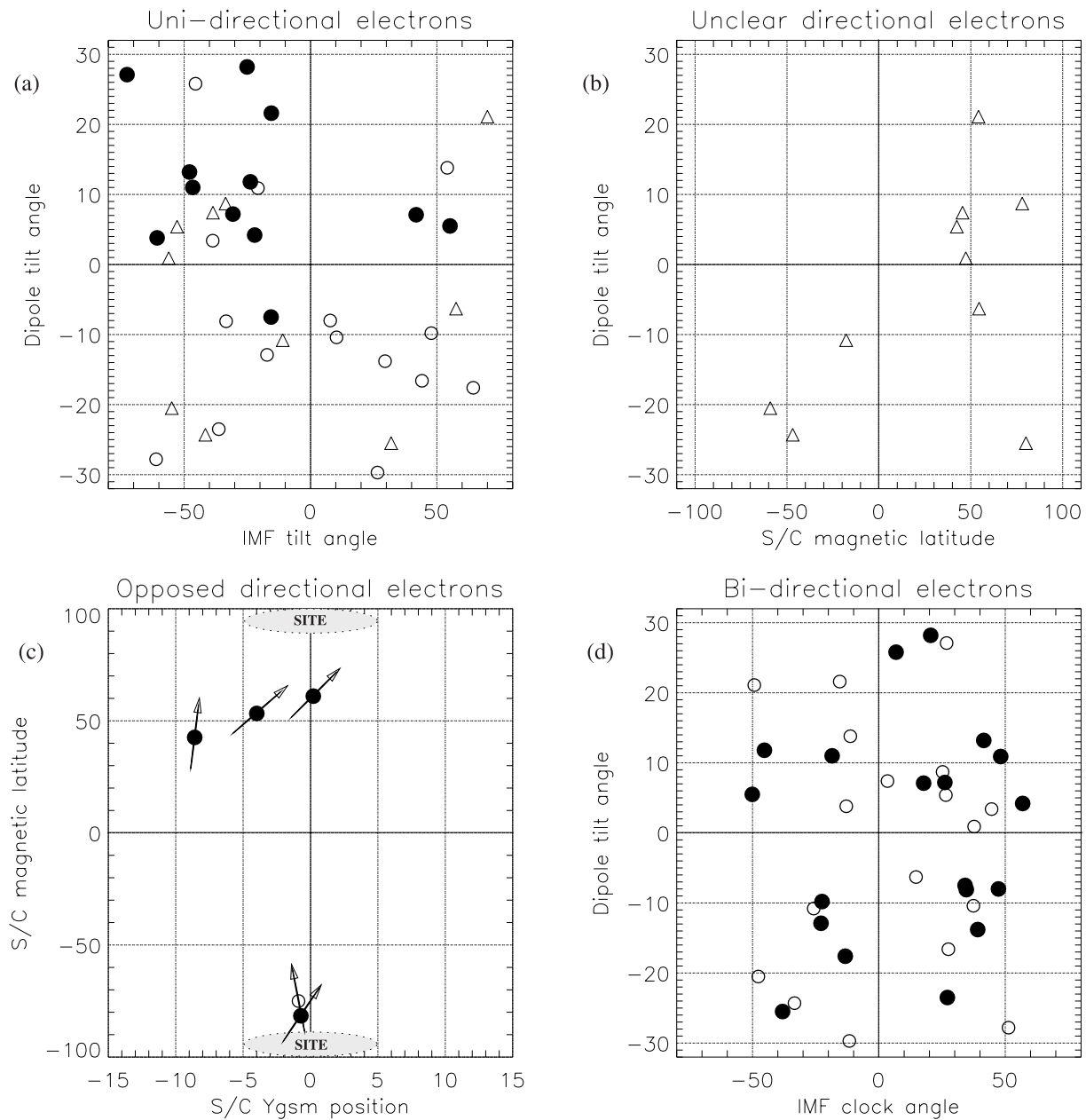


Figure 4. Scatterplots of the magnetopause passes and magnetosheath electron boundary layer characteristics from spacecraft 3 (c.f. Table 1). In Figures 4a, 4b, and 4d the y-axis corresponds to the actual dipole tilt angle at the time of magnetopause crossing. (a) The x-axis is the average IMF tilt angle in the $(X,Z)_{\text{GSM}}$ plane (see text). Open (solid) circles correspond to events showing a layer of parallel (antiparallel) heated electrons outside the magnetopause, thus implying the southern (northern) hemisphere may have reconnected first. The open triangles represent the unclear cases. (b) The x-axis shows the magnetic latitude (GSM) of spacecraft 3 for the ten unclear events (triangles). (c) GSM location of the five events showing electron streaming directionality opposed to that expected if the dipole tilt controls the hemisphere of initial reconnection. Filled (open) circles correspond to events showing the presence of unidirectional heated electrons outside the magnetopause coming from the opposite (current) hemisphere. The arrows through each point show the average IMF clock angle during that magnetopause crossing. (d) The x-axis is the average IMF clock angle. Filled circles correspond to events apparently showing the presence of bidirectional heated electrons outside the magnetopause. Open circles correspond to unclear cases.

observed, there is a strong tendency for crossings occurring with a positive dipole tilt angle to show antiparallel heated electron flow and crossings for negative dipole tilt angles to show parallel flow. As illustrated in Figure 1, this association is what would be expected if the dipole tilt angle determines the hemisphere in which a magnetosheath field line first reconnects. Only five out of the 27 directional events were clearly inconsistent (“opposed”) with this expectation, and those are indicated by “opp” in the “e- dir” column of Table 1.

[26] By contrast, Figure 4a also shows that the IMF tilt angle does not seem to order the electron directionality significantly, in the sense that positive (negative) angles do not generally lead to the southern (northern) hemisphere being reconnected first. Its effect thus appears limited. This finding may indicate that the passage through the bow shock and subsequent magnetic field draping at the dayside magnetopause partially removes the influence of the IMF tilt angle on the location of initial reconnection of a given magnetosheath field line.

3.3. Effect of the Magnetosheath Boundary Layer Thickness

[27] Further inspection of Table 1 reveals that 19 events, out of the 27 events showing a main directionality, show the presence of unidirectional heated electrons flowing parallel (antiparallel) to the magnetic field in the northern (southern) hemisphere. This corresponds to heated electrons originating from the hemisphere opposite to that of (in situ) observation. This finding may be the result of a larger thickness (and therefore an easier detection) of the magnetosheath boundary layer when observed in the hemisphere opposite to that reconnecting first.

[28] It is seen in Table 1 that five out of the seven unclear events occurring in the northern hemisphere are characterized by a positive dipole tilt angle. Similarly, the three unclear events from the southern hemisphere took place when the dipole tilt was negative. This characteristic is displayed in Figure 4b, where we plot the ten unclear events as a function of the dipole tilt angle and the spacecraft magnetic latitude (GSM) at the time of the magnetopause crossings. The latter serves as an indication of the hemisphere of observation. These conditions (for eight out of ten events in total) correspond to cases when reconnection would be expected to occur in the hemisphere of observation if the dipole tilt angle is the main factor controlling the hemisphere of initial reconnection. The fact that most of the unclear events occur for conditions where the hemisphere of observation would be expected to reconnect first is consistent with the possibility that the thickness of the boundary layer is increased in the hemisphere opposite to that of initial reconnection, thus allowing for an easier detection.

3.4. Characteristics of the “Opposed” Directional Events

[29] The above results have shown that the heated electron directionality outside the magnetopause is usually compatible with the dipole tilt controlling the location of initial reconnection of a given magnetosheath field line. However, it may be that in some cases a combination of the spacecraft location on the magnetopause (and in particular in the dawn-dusk direction) and the IMF clock angle

orientation would preclude the observation of field lines connected to one or the other hemisphere.

[30] This expectation stems from the fact that for a given IMF orientation (clock angle), only certain magnetosheath flux tubes will have the opportunity to make contact with the high-latitude magnetopause in a location favorable to reconnection in one or the other hemisphere (assuming the conditions for reconnection are limited to nearly antiparallel magnetic fields [Crooker, 1979]). The spacecraft may or may not be in the flow path of flux tubes that have had the opportunity to reconnect in one particular hemisphere. In the hypothesis of nearly antiparallel reconnection, only for relatively small clock angles would any flux tube have the opportunity to reconnect with both hemispheres. Thus for example, flux tubes passing over the northern dawn quadrant of the magnetopause would presumably only have been able to reconnect in the northern hemisphere if the IMF clock angle is not too large and positive. Similarly, for the same location and moderately negative clock angle, it would be possible that certain flux tubes may not have had the opportunity to reconnect in the northern hemisphere but would have reconnected in the southern hemisphere. This observational bias would apply independent of the dipole tilt angle.

[31] Figure 4c displays the orientation of the average IMF clock angle of the five “opposed” events (Table 1) as a function of the spacecraft magnetic latitude and Y position (in GSM). The filled circles represent events for which heated electrons are detected coming from the opposite hemisphere. Only one event sees the heated electrons coming from the hemisphere of observation (the open circle). The three events occurring in the northern hemisphere are located in the dawn quadrant, and all of them have positive IMF clock angles (directed toward dusk). The above bias is thus not relevant for these cases since, for these field orientations, one would expect the spacecraft to be able to see the signature of reconnection coming from perhaps both hemispheres but not from only the southern. The reason why the heated electrons in the boundary layer are coming from the southern hemisphere during these events is thus unclear. The two events in the southern hemisphere are close to noon and have relatively small IMF clock angles, so the above bias again can not explain the observed streaming direction. Thus the observational bias expected from the combination of spacecraft location and IMF clock angle does not seem to produce the “opposed” events.

3.5. Occurrence of Double High-Latitude Reconnection

[32] Figure 4d shows the distribution of the occurrence of bidirectional heated electrons in a scatterplot of the dipole tilt and IMF clock angles. Filled circles represent the events for which bidirectional heated electrons have been detected outside the magnetopause. Bearing in mind the above reservations (c.f. section 2.3), we find that 19 events (out of 37) show the possible presence of newly closed magnetosheath magnetic field lines outside the magnetopause. As observed in this plot, the distribution shows no clear dependence on either the dipole tilt angle or the IMF clock angle. Recall, however, that our survey is limited to events with average IMF clock angles between -60° and 60° .

[33] From Table 1 it appears that only one event thought to show bidirectional heated electrons outside the magnetopause did not also show clear evidence for a boundary layer of unidirectional electrons. This fact suggests that the identification of bidirectional heated electrons is associated with the definitive presence of a magnetosheath boundary layer and therefore of a reconnected magnetopause.

[34] Magnetosheath magnetic field piling at the dayside magnetopause under northward IMF could produce a maximum in the magnetic field strength near the subsolar magnetopause. Heated magnetosheath electrons could be reflected there and eventually return to the spacecraft at high latitudes (for either hemisphere), producing either bidirectional or unclear events. The extent to which such a scenario may affect our count of doubly reconnected field lines cannot be inferred from the present survey. The occurrence of potentially newly closed field lines will be given more detailed, careful attention in the near future.

4. Conclusions

[35] Using Cluster data we have studied the statistical properties of the magnetosheath electron boundary layer at the high-latitude dayside magnetopause under northward IMF. We have searched for the presence of both unidirectional and bidirectional heated electrons outside of the magnetopause. We particularly focused on the dependence of the detection of such unidirectional heated electrons on the dipole tilt and IMF tilt angles. The statistical findings strongly suggest that it is primarily the magnetic dipole tilt angle that controls the directionality of such heated electrons. By contrast, the effect of the IMF tilt angle appears marginal. The former result suggests that the dipole tilt angle determines in which hemisphere high-latitude reconnection may occur first, while the latter may indicate that the potential effect of the IMF tilt angle is partially removed by passage through the bow shock and subsequent draping at the dayside magnetopause. In addition, the strong correlation between the directionality of the heated electrons and the geomagnetic dipole tilt may imply a high reconnection occurrence rate at the high-latitude magnetopause, compatible with a recent study by Twitty *et al.* [2004].

[36] Although some reservations were noted regarding the determination of whether a given interval is inside or outside the magnetopause, the frequent detection of bidirectional heated electrons outside the magnetopause suggests that magnetosheath field lines may commonly reconnect in both hemispheres. Such a mechanism would allow for low-latitude boundary layer and possibly cold, dense plasma sheet formation under northward IMF.

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References

- Balogh, A., *et al.* (2001), The Cluster magnetic field investigation: Overview of in-flight performance and initial results, *Ann. Geophys.*, **19**, 1207–1217.
- Crooker, N. U. (1979), Dayside merging and cusp geometry, *J. Geophys. Res.*, **84**, 951–959.
- Eastman, T. E., and E. W. Hones Jr. (1979), Characteristics of the magnetospheric boundary layer and magnetopause layer as observed by IMP 6, *J. Geophys. Res.*, **84**, 2019–2028.
- Fuselier, S. A., B. J. Anderson, and T. G. Onsager (1997), Electron and ion signatures of field line topology at the low-shear magnetopause, *J. Geophys. Res.*, **102**, 4847–4863.
- Gosling, J. T., *et al.* (1991), Observations of reconnection of interplanetary and lobe magnetic field lines at high-latitude magnetopause, *J. Geophys. Res.*, **96**, 14,097–14,106.
- Hall, D. S., C. P. Chaloner, D. A. Bryant, D. A. Lepine, and V. P. Tritakis (1991), Electrons in the boundary layers near the dayside magnetopause, *J. Geophys. Res.*, **96**, 7869–7891.
- Johnstone, A. D., *et al.* (1997), PEACE: A plasma electron and current experiment, *Space Sci. Rev.*, **79**, 351–398.
- Kessel, R. L., *et al.* (1996), Evidence of high-latitude reconnection during northward IMF: Hawkeye observations, *Geophys. Res. Lett.*, **23**, 583–586.
- Lavraud, B., *et al.* (2002), Cluster observations of the exterior cusp and its surrounding boundaries under northward IMF, *Geophys. Res. Lett.*, **29**(20), 1995, doi:10.1029/2002GL015464.
- Lavraud, B., A. Fedorov, E. Budnik, A. Grigoriev, P. J. Cargill, M. W. Dunlop, H. Rème, I. Dandouras, and A. Balogh (2004a), Cluster survey of the high-altitude cusp properties: A three-year statistical study, *Ann. Geophys.*, **22**, 3009–3019.
- Lavraud, B., *et al.* (2004b), The exterior cusp and its boundary with the magnetosheath: Cluster multi-event analysis, *Ann. Geophys.*, **22**, 3039–3054.
- Le, G., C. T. Russell, J. T. Gosling, and M. F. Thomsen (1996), ISEE observations of low-latitude boundary layer for northward interplanetary magnetic field: Implications for cusp reconnection, *J. Geophys. Res.*, **101**, 27,239–27,249.
- Mitchell, D. G., F. Kutchko, D. J. Williams, T. E. Eastman, L. A. Frank, and C. T. Russell (1987), An extended study of the low-latitude boundary layer on the dawn and dusk flank of the magnetosphere, *J. Geophys. Res.*, **92**, 7394–7404.
- Ogilvie, K. W., R. J. Fitzenreiter, and J. D. Scudder (1984), Observations of electron beams in the low-latitude boundary layer, *J. Geophys. Res.*, **89**, 10,727–10,732.
- Onsager, T. G., J. D. Scudder, M. Lockwood, and C. T. Russell (2001), Reconnection at the high latitude magnetopause during northward interplanetary magnetic field conditions, *J. Geophys. Res.*, **106**, 25,467–25,488.
- Paschmann, G., W. Baumjohann, N. Sckopke, T. D. Phan, and H. Luehr (1993), Structure of the dayside magnetopause for low magnetic shear, *J. Geophys. Res.*, **98**, 13,409–13,422.
- Phan, T. D., *et al.* (1997), Low-latitude dusk flank magnetosheath, magnetopause, and boundary layer for low magnetic shear: Wind observations, *J. Geophys. Res.*, **102**, 19,883–19,895.
- Raeder, J., *et al.* (1997), Boundary layer formation in the magnetotail: Geotail observations and comparisons with a global MHD simulation, *Geophys. Res. Lett.*, **24**, 951–954.
- Rème, H., *et al.* (2001), First multispacecraft ion measurements in and near the Earth's magnetosphere with the identical CLUSTER Ion Spectrometry (CIS) Experiment, *Ann. Geophys.*, **19**, 1303–1354.
- Russell, C. T., G. Le, and S. M. Petrinec (2000), Cusp observations of high and low latitude reconnection under northward IMF: An alternate view, *J. Geophys. Res.*, **105**, 5489–5495.
- Song, P., and C. T. Russell (1992), Model of the formation of the low-latitude boundary layer for strongly northward interplanetary magnetic field, *J. Geophys. Res.*, **97**, 1411–1420.
- Szita, S., A. N. Fazakerley, P. J. Carter, A. M. James, P. Travnicek, G. Watson, M. Andre, A. Eriksson, and K. Torkar (2001), Cluster PEACE observations of electrons of spacecraft origin, *Ann. Geophys.*, **19**, 1721–1730.
- Twitty, C. K., T. D. Phan, G. Paschmann, B. Lavraud, H. Rème, and M. W. Dunlop (2004), Cluster survey of tailward-of-the-cusp reconnection and its IMF dependence, *Geophys. Res. Lett.*, **31**, L19808, doi:10.1029/2004GL020646.

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